Postprint: Measurements of Stray Light and Spatial PSF for the Multi-band Spectrometer of the 1-meter New Vacuum Solar Telescope

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Abstract

Stray light, arising from scattering by optical surfaces and the Earth' s atmosphere, degrades the spatial resolution of spectral images. All optical systems exhibit stray light; suppressing it is essential for obtaining high-resolution spectral images. The stray light in multi-band spectrometers can be categorized into two types: (1) stray light caused by opto-mechanical structures within the spectral barrel; (2) stray light that mixes into the imaging optical path and participates in dispersion. The first type can be directly measured, constituting approximately 3% of the spectral energy. The second type is difficult to measure accurately due to multiple influencing factors. Solar eclipse spectral measurements have determined that the lower limit of stray light from the surroundings of an observed target onto the target itself is approximately 10%, and the spatial point spread function has been measured to provide a reference for high-resolution spectral reconstruction.

Full Text

Stray-Light Measurement of the Multi-band Spectrometer of the 1-meter New Vacuum Solar Telescope

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Abstract

Stray light, caused by scattering from optical surfaces and the Earth' s atmosphere, degrades the spatial resolution of spectral images. Since virtually all optical systems suffer from stray light, its suppression is essential for obtaining high-resolution spectral data. The stray light in the multi-band spectrometer can be divided into two categories: (1) stray light generated by scattering from optical and mechanical structures within the spectral barrel, and (2) stray light that mixes into the imaging optical path and participates in dispersion. The first category can be measured directly and accounts for approximately 3% of the spectral energy. The second category is difficult to measure precisely due to numerous influencing factors. From eclipse spectral measurements, we determined that the lower limit of stray light produced around the observation target is about 10%. We also measured the point spread function (PSF) in the spatial direction, providing a reference for future high-resolution spectral reconstruction.

Keywords: 1m New Vacuum Solar Telescope; Multi-band Spectrometer; Stray Light; PSF

1. Introduction

The 1-meter New Vacuum Solar Telescope (NVST) is primarily used for high-resolution imaging observations of the solar photosphere and chromosphere, as well as for solar spectroscopic observations [**?**]. As the largest ground-based vacuum solar telescope in China, the NVST faces significant challenges from stray light, which substantially affects both imaging and spectroscopic observations. In spectral observations, stray light can constitute a large fraction of the spectral intensity, severely impacting observations of sunspots, the solar limb, and deep absorption lines [**?**]. The influence is particularly pronounced for faint targets, where stray light can dominate the measured signal and compromise data analysis.

The sources of stray light in ground-based telescopes include: (1) scattering by dust and particles in Earth' s atmosphere, (2) time-varying stray light caused by rapid fluctuations in atmospheric refractive index, and (3) instrumental scattering [**?**]. Based on its manifestation, stray light can be classified into two types: (1) dispersive stray light that passes through the grating and participates in dispersion, and (2) instrument stray light generated by scattering from optical and mechanical surfaces. The effects of stray light are typically quantified through the point spread function (PSF), which describes how a point source is spatially broadened by the optical system. Both large-scale and small-scale stray light can be expressed analytically using functions such as Gaussians, Lorentzians, or their combinations [**?**].

This paper theoretically divides the stray light in the multi-band spectrometer into instrument stray light and dispersive stray light, measuring each component separately. We also measure the spatial PSF and elucidate its relationship with stray light, using eclipse spectra to constrain the dispersive stray light component.

2. Theoretical Description of Stray Light

Solar radiation passing through Earth’ s atmosphere and the telescope system reaches the detector with an observed intensity I_{obs}. The true solar intensity I_{true} is convolved with the PSF:

$$I_{\text{obs}} = I_{\text{true}} \otimes \text{PSF}$$

For a time-invariant PSF, applying a Fourier transform yields:

$$\tilde{I}_{\text{obs}} = \tilde{I}_{\text{true}} \cdot K$$

where K represents the convolution kernel of the PSF and the tilde denotes Fourier transformation. The true spectral energy can then be recovered as:

$$I_{\text{true}} = \mathcal{F}^{-1}\left(\frac{\tilde{I}_{\text{obs}}}{K}\right)$$

A schematic diagram of the NVST multi-band spectrometer is shown in Figure 1 [?]. For measurement convenience, the spectral intensity at the detector center can be expressed as [?]:

$$I_{\text{obs}} = I_{\text{true}} + \text{dc} + \text{parasitic light} = \text{dc} + \alpha_{\text{global}}(I_{\text{global}}) + \beta$$

where I_{local} represents the spectral intensity from a point at spatial position (x, y) on the Sun, I_{global} denotes the average spectral intensity after the F3 focus, and α_{global} is the proportion of stray light contributed by the entire solar disk.

The I_{local} term contains stray light related to the target position and consists of two components: (1) light from the field of view that reaches the F3 focus after passing through pre-focus optical elements, and (2) stray light generated by the instrument PSF [?]:

$$I_{\text{local}} = \alpha_{\text{instr}}(\Delta) \times I_{\lambda} + \sigma(\Delta)$$

where Δ represents the area of the aperture stop at the F3 focus, and $\sigma(\Delta)$ represents the spatial PSF contribution after the F3 focus. For quiet-Sun regions without special structures, the two terms on the right side can use the same proportionality factor α.

Wavelength-independent stray light originates from within the spectral barrel and does not pass through the grating. Since it mixes with the incident light path, it is dispersed along with the main beam. This component is proportional to the amount of light entering the spectral barrel. The equation can effectively address the system stray light problem.

Because the contribution of stray light to I_{local} is significant and the average image profile at full field-of-view is similar to that of the entire solar disk, it is necessary to define I_{global} from the observed spectrum. The equation simplifies to [?]:

$$I_{\text{local}} = I_{\text{global}} + \alpha I + \beta$$

where β represents instrument stray light from scattering within the spectral barrel, and αI represents dispersive stray light from atmospheric scattering mixed into the imaging path. The measurement of parameters α and β is described in the following section.

3. Stray-Light Measurement

The NVST multi-band spectrometer operates at multiple wavelengths including Hα, Ca II, and Fe I. Before measuring stray light, we compared our observations with Fourier Transform Spectrograph (FTS) standard spectra [?]. After aligning the spectral lines, we convolved the FTS standard spectrum with a Gaussian profile. Using a Gaussian with half-width of 0.0065 nm produced good agreement with the observed line profiles. As shown in Figure 2, even after convolution, the observed average line profile remains shallower than the convolved standard spectrum, with the difference attributed to stray light.

3.1 Instrument Stray-Light Measurement

Instrument stray light arises from scattering by optical and mechanical structures within the spectral barrel. This component depends on the amount of light entering the barrel—the more light, the more stray light. Even small residual energies at line centers can affect spectroscopic observations.

We categorize instrument stray light into two types: (1) leaked stray light from light leaks in the barrel, and (2) scattered stray light from rays deviating from the main optical path. To measure leaked stray light, we obtained two sets of dark frames using different methods: one measuring only the detector' s dark current, and another with the F3 lens completely blocked to include both dark current and leaked stray light I_{leaked}. The intensity of I_{leaked} equals the average intensity of the dark frame with blocked F3 lens minus the average intensity of the dark frame alone [?]. The leaked stray light in each channel ranges from 0.3% to 0.5%.

To measure scattered stray light, we placed a sharp-edged metal blade to block part of the slit. After subtracting the dark frame, the spatial intensity distribution near the absorption line is shown in Figure 3. Figure 3(b) reveals residual intensity in the shadowed region after dark subtraction, which originates from instrument stray light.

The measurement principle is that when direct imaging light to the F4 focus is blocked, the remaining energy at F4 represents free-scattered light within the spectral barrel. We improved this method by assuming instrument stray light enters at various angles. For large-angle stray light, direct blocking is effective, while small-angle stray light is attenuated by scattering and absorption in the baffle tube.

The instrument stray-light intensity I_β is obtained by subtracting the average spectral intensity I_{obs2} (measured with baffle tube) from the normal observation intensity I_{obs}:

$$I_\beta = I_{\text{obs}} - I_{\text{obs2}}$$

The measured instrument stray-light levels are 3.5% for Hα, 0.5% for Ca II, and 8.8% for Fe I channels, significantly higher than typical stray-light levels. Table 1 summarizes all measured stray-light components.

Measurement results of stray light

Channel	Wavelength (nm)	Leaked Stray Light	Instrument Stray Light
Hα	656.3	0.4%-0.6%	3.5%
Ca II	532.4/656.3/854.2	0.4%-0.6%	0.5%
Fe I	532.4/656.3/854.2	0.4%-0.6%	8.8%

3.2 Dispersive Stray-Light Measurement

Dispersive stray light originates from atmospheric scattering of sunlight. Its magnitude is determined by comparing sunspot umbra spectra (which have intrinsically low intensity) with quiet-Sun spectra [**?**]. However, since sunspots still emit some radiation, we performed eclipse observations for more accurate measurement. During totality, the Moon itself emits no light, making the eclipse spectra ideal for determining the α parameter.

We acquired data at eclipse maximum with 70 ms exposure time, positioning the slit across the shadow edge. The eclipse spectrum for each channel is shown in Figure 5. By comparing the spectral profile near the shadow boundary with the normal solar spectrum profile, we determined that the remaining energy in the shadowed region is about 10% of the intensity on the solar disk, giving $\alpha \approx 10\%$.

4. Spatial Point Spread Function Measurement

4.1 Relationship Between PSF and Stray Light

In spectral observations, the PSF characterizes the instrument profile’ s effect on spectral images. After passing through the optical system, the light signal is modified by the PSF. Stray light affects the PSF profile, so measured PSFs are contaminated by stray light. However, once measured, the PSF can be used to restore the true spectral profile through deconvolution, improving spatial resolution and eliminating stray-light effects.

Adaptive Optics (AO) systems correct for stray light caused by atmospheric refractive index variations in real time, leaving only stray light from atmospheric scattering and instrumental scattering. Each point in the field-of-view scatters light to other points, creating mutual interference that forms stray light [?]. Deconvolution can enhance spatial resolution but amplifies noise.

4.2 PSF Measurement Method

We measured the spatial PSF of the multi-band spectrometer by blocking part of the field-of-view with a metal plate. Since the NVST is a vacuum telescope with its focus inside the vacuum chamber, we could only block the F3 focus. Figure 6 shows the spectral image with the slit blocked by the metal plate.

After removing instrument stray light and dark current, we analyzed the radial intensity variation. The curve differs from the ideal step function because the PSF spreads light beyond the blocked region. We constructed a PSF kernel combining Gaussian and Lorentzian functions, adjusting parameters using a trial-and-error method until convolution with a step function matched the observed intensity variation. The final kernel is shown in Figure 7.

The NVST multi-band spectrometer has a spatial resolution of 0.082 /pixel (0.82 total). The one-dimensional kernel derived from the two-dimensional axisymmetric kernel [?] is:

$$K(x) = \frac{dI}{dx}$$

where dI represents the observed intensity distribution variation relative to the step function. The trial-and-error kernel matches the data well, particularly in the tail of the intensity variation curve, confirming that the PSF is the primary source of stray light when only part of the field is illuminated.

5. Conclusion

Based on stray-light theory, we divided the stray light into instrument and dispersive components. Due to different detector positions for each channel, the stray-light proportion varies by wavelength: 3.5% for Hα, 0.5% for Ca II, and 8.8% for Fe I. The instrument stray light in the Fe I channel is significantly higher than normal levels. We measured the atmospheric scattering component using eclipse spectra and determined the spatial PSF of the NVST multi-band spectrometer, laying the groundwork for future stray-light removal algorithms and high-resolution spectral reconstruction.

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Note: Figure translations are in progress. See original paper for figures.